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Preliminary study of 50 W Class-E GaN FET amplifier for 6.78 MHz capacitive wireless power transfer

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Abstract

A preliminary study of Class-E radio frequency power amplifier for wireless capacitive power transfer (CPT) system is presented in this paper. Due to a limitation in coupling capacitance value, a high frequency operation of switching power inverter is necessary for the CPT system. A GaN MOSFET offers reliability and performance in a high frequency operation with an improved efficiency over a silicon device. Design specification related to the parallel load parameter, LC impedance matching and experimental analysis of the amplifier is explored. An experimental setup for the proposed inverter and its integration with the CPT system is provided, and the power efficiency is investigated. As a result, by utilizing a 6.78 MHz resonant frequency and a 50 Ω resistive load, 50 W of power has been transmitted successfully with an end to end system efficiency over 81 %. Additionally, above 17 W wireless power transfer was demonstrated successfully in the CPT system under 6 pF coupling with the efficiency over 70 %.

Keywords: Class-E power amplifier; wireless power transfer; capacitive power transfer; high efficiency; high frequency power source.

I. Introduction

In radio frequency (RF), a switching mode power supply (SMPS) plays an important rule since it is related to the system efficiency. Maximum power transfer efficiency can be obtained by minimizing dissipation of power which is mostly happening in power transistor. Class-D power amplifiers are usually chosen to convey the transmitter, but it requires at least two transistors to acquire zero voltage switching (ZVS), which increases product and process costs. A Class-E power amplifier is known as a great efficient power amplifier in RF. It uses a single-ended switching device that works with a resonant network between the switch and the load. The device is activated as an on/off switch and the parallel load network forms the voltage and current waveforms to avoid concurrent high voltage and high current in the transistor during the switching transitions. The conditions of zero current switching (ZCS) or zero voltage switching (ZVS) can be achieved easily.

An invention of Class-E power amplifier was conveyed by Nathan O. Sokal and Alan D. Sokal in 1972. While the details of publication were announced in 1975 [1] with a complete and comprehensive design also introduced [2]. Advance research and technology implemented the Class-E amplifier for wireless power transfer (WPT) application, from a low frequency [3] to a high

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frequency field [4] includes a charging applications [5][6]. Furthermore, research studies related to adaptive and controllable power combiner were also offered [7][8]. It is difficult to change the regeneration frequency due to the limitation of the ISM band for MHz WPT. Typically, a fixed frequency such as 6.78 MH which is the lowest frequency in the globally accepted ISM (industrial, scientific and medical) band is preferred. The ITU-R (International Telecommunication Union Radio Communications Sector) currently recommends this single frequency for wireless energy transmission from consumer devices, as it would have little or no negative impact on other licensed bands. A higher operating frequency in ISM band, such as 13.56 MHz or 27.12 MHz, can have further improved local freedom. However, it increases switching loss, driving loss and circuit design challenges (e.g. circuit board configuration and component selection) [9].

The most interesting method in WPT is using capacitance coupling interface or known as capacitive power transfer (CPT). Figure 1 shows the CPT basic diagram that consists of DC power supply and high frequency DC to AC power converter in the primary side (transmitter) of the CPT. A rectifier is needed to deliver the DC voltage and current to the load in the secondary side (receiver). CPT operates by using electric fields resonant in order to transfer the power wirelessly. Two couples of metal plate work as a capacitive interface between the primary and the secondary side. Several researches related to an implementation of the CPT have been conducted, such as biomedical sensor and implantable devices to a living object [10][11], drone application [12][13], and electric vehicle charging system [14][15].

Research and development of amplifier for WPT have been conducted by engineers. For inductive power transfer (IPT), as the famous method of WPT, an 80 % efficiency was obtained by implementing Class-E which has an operating frequency of 6.78 MHz and 20 W of power to 90 Ω load [16]. On the other hand, a WPT for battery charging application was carried out by using CPT [17]. It uses a Class-D topology of the inverter with frequency switches at 6.78 MHz, providing 4 of delivered power with efficiency over 76 %.

Research by [18] studies the Class-E implemented to the CPT system by generating 9 W power through 1.51 MHz switching amplifier. The efficiency of their inverter was 90.3 % with 2 mm gap and 8.3 loads. Its efficiency was higher than the Class-E on IPT system, but less power delivered to the load. Moreover, its frequency was lower than the allowed level by the ISM band regulation. IPT system having an ability to transfer at a longer distance was achieved by [19] and [6] using 6.78 MHz Class-E power amplifier, with delivered power over 10 W and 16.3 W, respectively, providing an efficiency over 70 % and 74.2 %, accordingly. These selected researches in power amplifier for WPT applications can be seen in Table 1.

In this paper, a 50 W high frequency power amplifier is proposed by using the topology of Class E with an operating resonant frequency of 6.78 MHz. Preliminary design and experiment include an implementation of wireless power transfer by using a capacitive coupling interface are pronounced. The structure of this paper will be divided as follows: Section II describes the proposed Class-E power amplifier related to the design specification of parallel load components, impedance circuit and power efficiency identification. The fabrication, the characteristics analysis, and the measured results of the amplifier are discussed in Section III. Finally, the conclusions are presented in Section IV.

II. Materials and Methods

A. Proposed Class-E RF power amplifier

Circuit diagram of a Class-E RF power amplifier with impedance matching network to 50 Ω load is

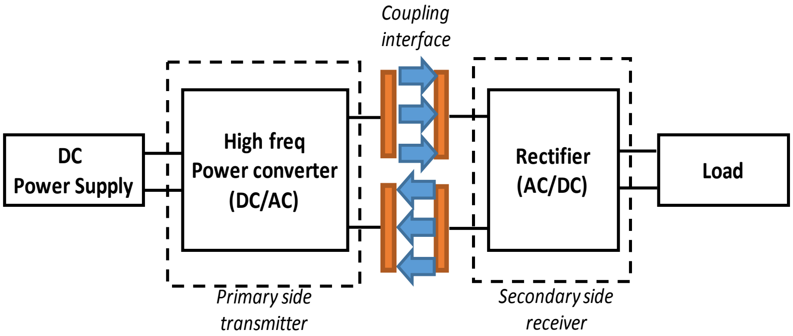

Figure 1. Basic diagram of a capacitive wireless power transfer [9]

Table 1.
Selected researches in power amplifier for WPT applications

Ref	Year	Topology	Frequency (MHz)	Power Out (W)	Gap (mm)	Load (Ω)	WPT Method	Efficiency (%)
[16]	2015	Class-E	6.78	20	n.a.	90	IPT	80
[17]	2015	Class-D	6.78	4	0.04	Battery	CPT	76
[18]	2016	Class-E	1.51	9	2	8.3	CPT	90.3
[19]	2019	Class-E	6.78	10	22	10	IPT	70
[6]	2020	Class-E	6.78	16.3	40	20	IPT	74.2

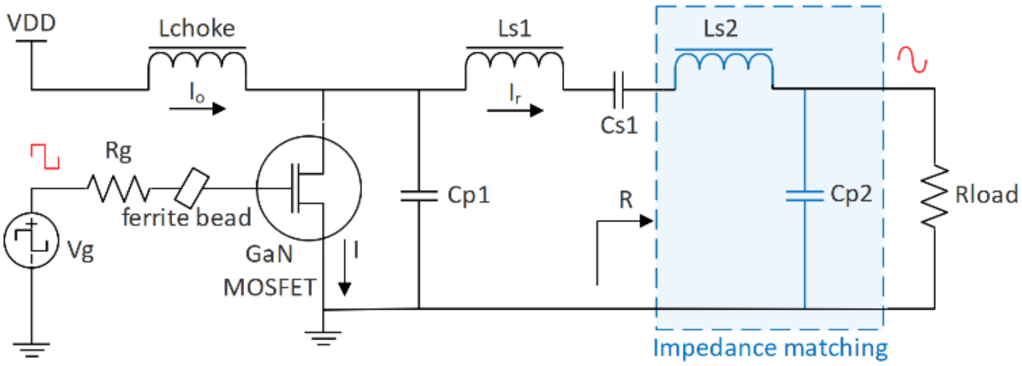

Figure 2. Circuit of Class-E power amplifier with impedance matching network

presented in Figure 2. A GaN based MOSFET is used as the switching transistor since it can operate with low on-resistance at high frequency. The parallel load network consists of a DC choke inductor, L_{Choke}, a parallel shunt capacitor, C_{P1}, a series connected resonant inductor, LS1 and capacitor, C_{S1}. The impedance matching circuit contains a series inductor, L_{S2}, and a parallel capacitor, C_{P2}, and a (commonly 50 Ω or 75 Ω) load.

B. Parallel load network specification

In order to attain a working properly of switching transistor operation, an optimal parameters of the parallel load network have to be calculated well as described by [2]. With the condition of 50 % duty cycle, the output impedance of the inverter, R, can be assimilated using Equation (1) by [20].

$$R = \left(0.577 \times V_{DD}{}^{2}\right) / P_{OUT} \tag{1}$$

where V_{DD} is the voltage biased at drain MOSFET and P_{OUT} is the output power of the designed inverter. A perfect switching transition is rolled by the value of shunt capacitor, C_{P1}, which is obtained by using Equation (2):

$$C_{P1} = 0.685 / (\omega \times R), \tag{2}$$

and, the value of DC choke inductor, L_{Choke} can be calculated by using Equation (3):

$$L_{Choke} = 0.732 \times R / \omega. \tag{3}$$

The series resonant inductor L_{S1} and capacitor C_{S1}, can be acquired by using Equations (4) and (5):

$$L_{S1} = Q \times R / \omega. \tag{4}$$

$$C_{S1} = 1 / (Q \times R \times \omega). \tag{5}$$

where $\omega = 2\pi f$, is the angular frequency of the designed amplifier. R and Q mention the output impedance of the inverter and the load quality factor, respectively. Its chosen value is a trade-off concerning [2]:

- The operational bandwidth, which is wider with lower Q value,
- The harmonic content of the output power, that will be lower with a higher Q, and
- The power loss of the parasitic resistances in series resonant, which is lower while lower Q.

C. Impedance matching

Since most power supply and measurement tools are designed to match to common 50 Ω or 75 Ω, then the impedance matching component which is capacitor CP2 and inductor LP2 can be expected approximately by using Equations (6) and (7):

$$C_{P2} = \frac{1}{\omega \times R_{LOAD}} \sqrt{\frac{R_{LOAD}}{R} - 1} \tag{6}$$

$$L_{S2} = C_{P2} \times R \times R_{LOAD} \tag{7}$$

D. Power and efficiency

The output power is reflected from the acquired load voltage V_{Load} over the resistive load R_{Load}. While the generated input power is obtained from the DC power source by multiplication of the input DC voltage V_{DD} and current I_O. From this condition, the power efficiency is then can be calculated by using Equation (8):

$$Eff\,(\%) = \frac{P_{OUT}\,(\mathrm{W})}{P_{IN}\,(\mathrm{W})} = \frac{V_{LOAD}{}^{2}\,(\mathrm{V}^{2}) / R_{Load}\,(\Omega)}{V_{DD}\,(\mathrm{V}) \times I_{O}\,(\mathrm{A})} \tag{8}$$

The accepted voltage VDD in order to determine the power capability of Class-E RF amplifier can be calculated by using Equations (9) and (10):

$$V_{BV} \geq 3.65 \times V_{DD}, \tag{9}$$

$$I_{DS\max} = 2.86 \times I_{O}. \tag{10}$$

where V_{BV} and $I_{DS\max}$ are the breakdown voltage and current flow to the FET, respectively. However, because of the load and coupling variations, the peak voltage across the device can be as high as 7 times the supply voltage [20].

III. Results and Discussions

This section will give detail results and discussion related to the hardware experiment of the proposed Class-E amplifier in delivering the power to the CPT system. The proposed and fabrication of multi-resonant frequency Class-E RF power amplifier are shown in Figure 3 and Figure 4, respectively. The inverter system consists of: an external voltage terminal (a) that is connected to a switching mode power supply (SMPS) (b) which works rectifying 110 VAC to 24 VDC. The output DC

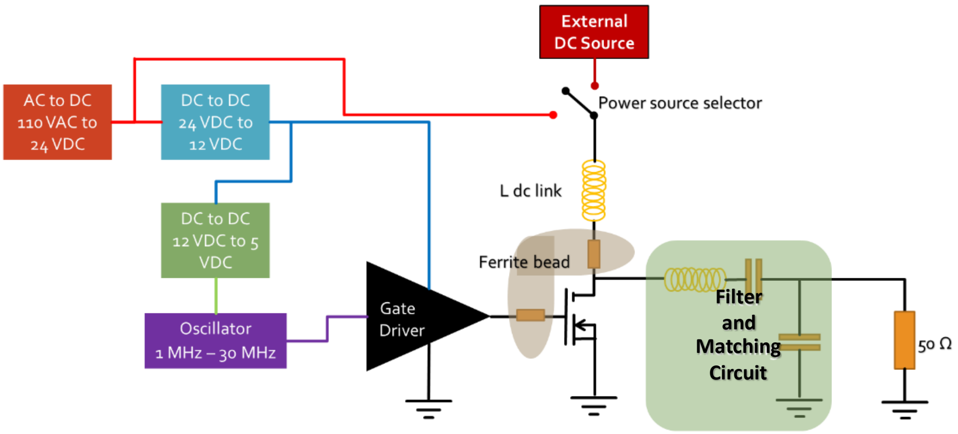

Figure 3. Proposed multi-resonant frequency Class-E RF power amplifier

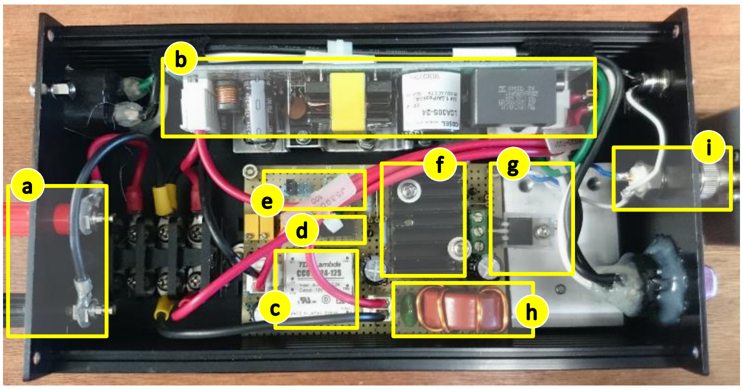

Figure 4. Fabrication of 6.78 MHz Class-E RF power amplifier: (a) external V_{DD}; (b) AC/DC power rectifier; (c) 24 V to 12 V DC-DC converter; (d) 12 V to 5 V DC-DC converter; (e) multi resonant frequency oscillator; (f) gate driver; (g) GaN MOSFET; (h) choke inductor; and (i) RF output

voltage can be used as internal drain supply voltage when only 24 V needed by the system. Moreover, the voltage is supplied to the isolated DC-DC converter that produces a 12 V (c) for gate driver supply voltage and 5 V (d) for the oscillator supply voltage. A multi-resonant oscillator (e) is used to provide a variable operating frequency depending on the system needed. A single gate driver (f) with a heat sink attached is then connected to the switching GaN MOSFET (g) where its body coupled to the large heat sink. A DC link inductor can be seen in (h) part, while the RF output of the inverter is joined to the LC impedance matching network through a Bayonet Neill-Concelman (BNC) connector. By following the design specification in Section II, a detail list of design index and parameter of the proposed Class-E RF power amplifier is presented in Table 2.

The experiment is carried out by investigating the effect of drain bias voltage changes to the efficiency of the inverter. The testing setup is divided into two schemes, that only Class-E RF power amplifier T (device under test, DUT) connected directly to the 50 Ω resistive load, as the first shown in Figure 5. An external DC power source is used and connected to the amplifier external source terminal. The RF output terminal DUT uses a BNC connector, is coupled to the matching network circuit. In the end, the 50 Ω resistive load is attached to the output terminal of the network. The gate driver, the drain output and the load voltage signals are connected to the Tektronix mixed signal oscilloscope MSO 4034 by utilizing the voltage probe cable. The second scheme is integrating the inverter to the CPT system in order to transfer the power wirelessly. Further explanation will be provided in section D related to the power transfer efficiency.

A. Gate driver's signal oscillation characteristics

Figure 6 illustrates the output signal from the oscillator IC LTC 1799. It can be observed that a clear square wave signal is produced by the IC. Even though there are some noises appeared, this signal still succeeds to trigger the gate of switching MOSFET. A pure sinusoidal waveform is measured at the load resistance 50 Ω with 80 V and 20 V of the peak to peak load voltage and drain voltage operation, respectively.

B. Drain voltage characteristics

The characteristics of the output signal produced from the MOSFET drain pin V_{Drain}, load voltage V_{Load} and current I_{Load} are drawn in Figure 7. The peak to peak drain-source voltage V_{Drain} is measured at 182 V. The wide-ranging load voltage and current amplitudes of the amplifier are exposed with almost pure sinusoidal waveform at 132 V and 2.8 A peak to peak, correspondingly. This condition is satisfied when the DC source power 55 W and the ideal resistive load 50 Ω.

Table 2.
Design index and parameter list of the 6.78 MHz Class-E RF power amplifier

Parameter (Figure 4)	Components/Value/Type
External V_{DD} (a)	External supply voltage
AC to DC power rectifier (b)	AC/DC 110 VAC to 24 VDC SMPS
DC to DC converter (c)	CCG152412S TDK-Lambda, Isolated 15.6W, 9-36 V_{in} 12 V_{out} 1.3 A
DC to DC converter (d)	TRACO TME 1205S Isolated single output
Oscillator (e)	LTC1799, 1 MHz – 30 MHz
Gate driver (f)	EL7104 single channel
MOSFET (g)	TPH3212PS 650V GaN FET
Output power, P_{Out}	60 W
Resonant frequency, f	6.78 MHz
DC link voltage, V_{DD}	30 V
DC link (choke) inductor (h), L_{Choke}	3.35 μH
Series inductor, $L_{S1} + L_{S2}$	1.32 μH
Series capacitor, C_{S1}	1040 pF
Matching capacitor, C_{P2}	690 pF

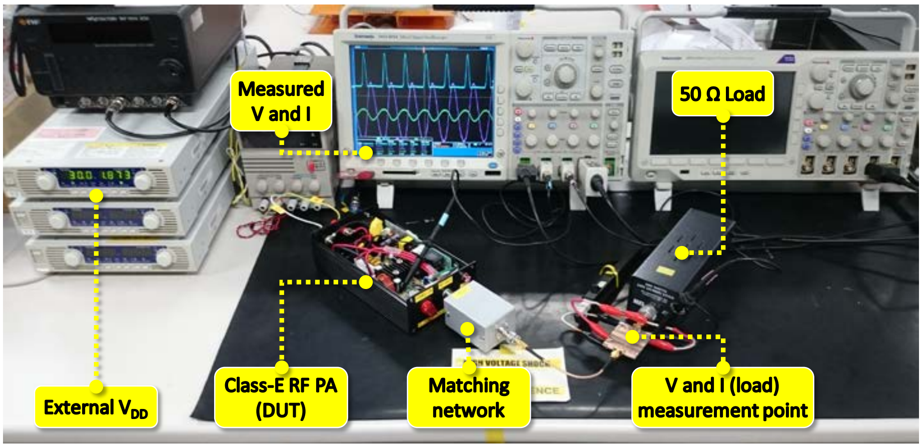

Figure 5. Experimental setup of Class-E RF power amplifier amplifier

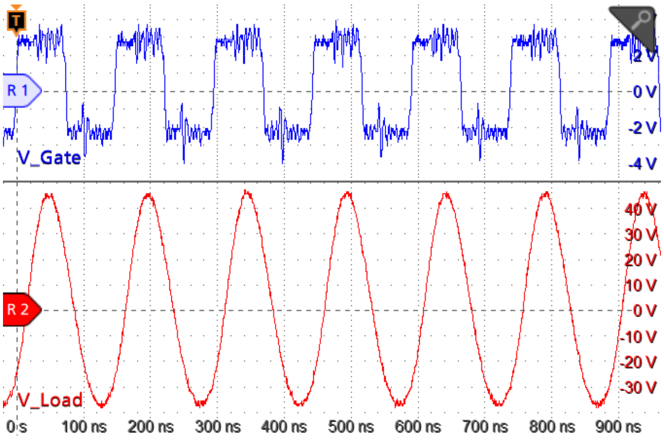

Figure 6. Gate driver signal oscillation of 6.78 MHz Class-E RF power amplifier

C. Load voltage characteristics

The load voltage characteristic with different input voltage to the drain of the MOSFET is evaluated. Figure 8 illustrates the load voltage signal obtained by generating a changed voltage to the V_{DD} terminal. It can be seen that with the increasing of V_{DD} value will result in a higher amplitude of load voltage. The maximum value of V_{DD} is limited by the switch device breakdown voltage V_{BV} value that defined by the Equation (9).

D. Power and efficiency characteristics

Class-E amplifier works in the specific resonant frequency determined by its components. The response frequency for power characteristic of the amplifier is shown in Figure 9 where, from 4 to 6 MHz of frequency, the delivered power slightly increases from the level of 28 W to 55 W. The inverter delivers power over 56 W when the frequency is in resonant of 6.78 MHz. Moreover, the power is decreased linearly for the frequency operation above 7 MHz.

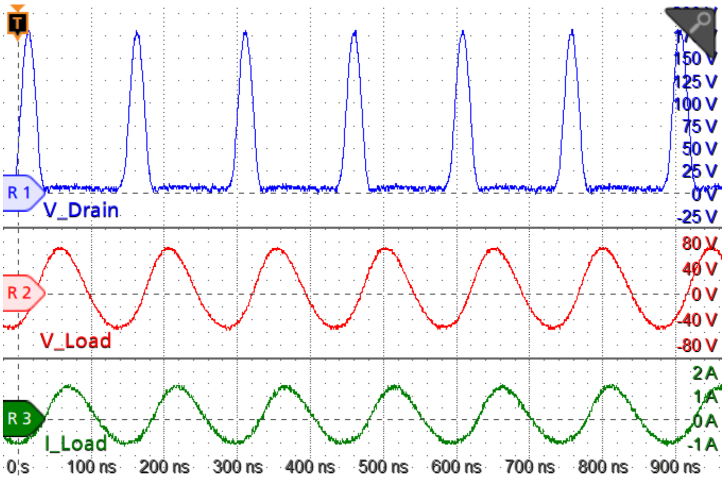

Figure 7. Drain voltage characteristic of 6.78 MHz Class-E RF power amplifier

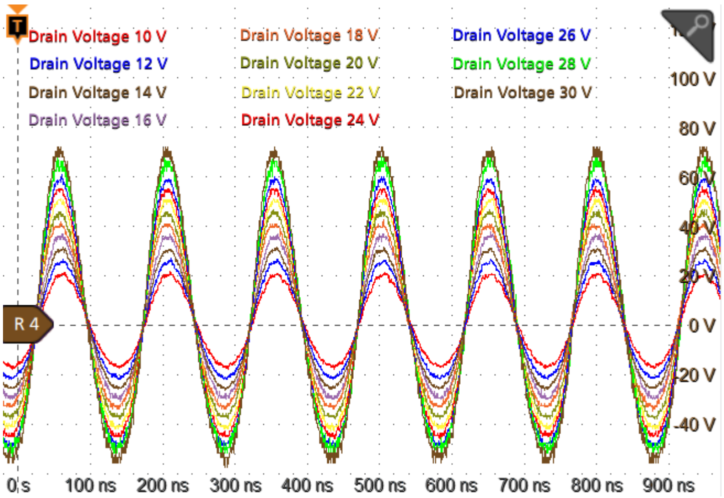

Figure 8. Load voltage characteristic with different drain voltage conditions

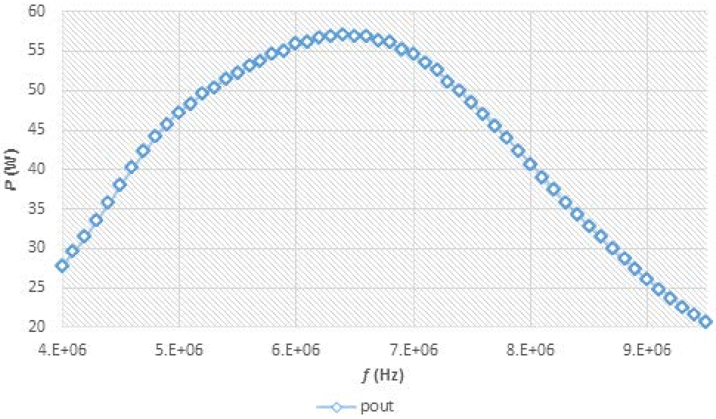

Figure 9. Frequency response of Class-E RF amplifier

Figure 10 illustrates the power and efficiency of the proposed Class-E RF power amplifier with the change of VDD value from 10 V until 36 V in the incremental order of 2 V. While the voltage starts increasing from 10 V to 20 V, the efficiency is improved slightly from the level 61 % up to 78 %. On this condition, the output power is distributed successfully from 5 W to 25 W. Moreover, when the output power from 30 W up to 60 W is delivered, the inverter can maintain the efficiency to the level over 80 % with the value of V_{DD} is settled from 22 V to 32 V. In the case of V_{DD} over 32 V, the efficiency of inverter is reduced dramatically to the level of 72 % with the conveyed power touch to 75 W. Since the VDD increased, the current flowing to the choke inductor and switch is proportionally increases. From Figure 10, it can be seen that the input power is increased gradually compared to linearly for the output power. A higher current flows to the magnetic core inductor produces eddy current loss, furthermore, heat occurs to the core.

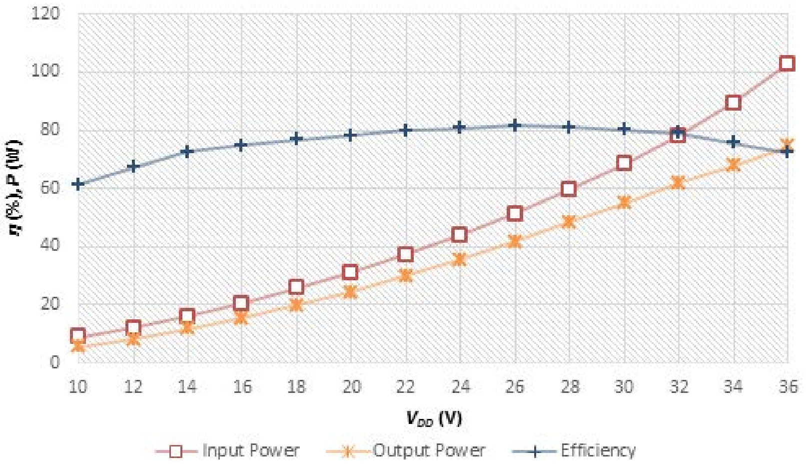

Figure 10. Power and efficiency characteristics of 6.78 MHz Class-E RF amplifier amplifier

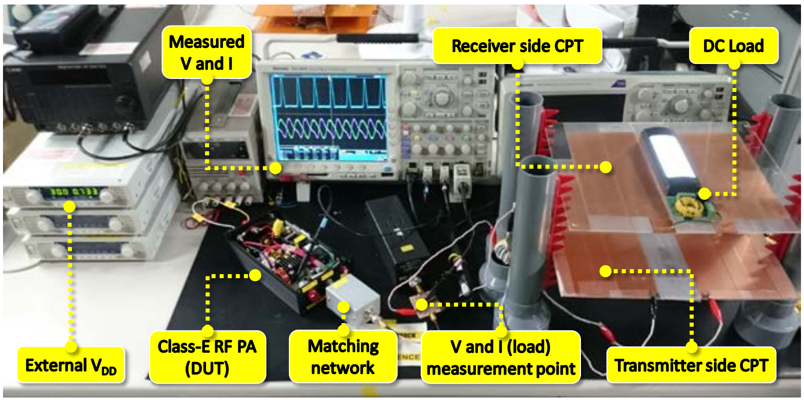

Figure 11. Experimental setup of capacitive wireless power transfer

Figure 11 describes the experimental setup of Class-E RF power amplifier integrated with the capacitive wireless power transfer. The setup consists of an external power supply that connected to the external source terminal of the DUT. A matching circuit is linked to the RF output terminal of the inverter, then connected to the step-up transformer in order to increase the RF amplitude. At this point, the output of the transformer attaches to the coupling plate interface of CPT as a transmitter side. The receiver side consists of a commercial DC load having 50 Ω contains of LED, is connected to the step-down transformer and full bridge rectifier diode that converts the AC sinewave into DC voltage.

The efficiency of the Class-E RF power amplifier that is integrated into the CPT system is shown in Figure 12. It can be viewed that the efficiency is having a reduction from the highest level 81 % to 70 % of the capacitive wireless power transfer in comparison with 6.78 MHz Class-E RF power amplifier. The load in CPT system is powered wirelessly through a 6 pF coupling interface with the measured value 16.8 W and 24 W of the output power and the input power, correspondingly. Meanwhile, the Class-E itself can have an efficiency value of 81 % with the measured power 60 W and over 50 W of the input power and the output power, respectively.

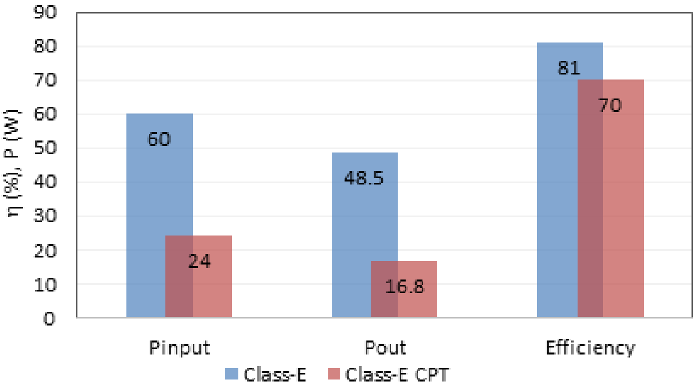

Figure 12. Power and efficiency of 6.78 MHz Class-E RF with CPT system

The power loss of the Class-E amplifier can be referred to the inductors and capacitors parasitic resistance, as an equivalent series resistance (ESR). The other cause is due to manual fabrication of the inductors in which affect to the unmatched impedance network.

IV. Conclusion

This paper has presented a preliminary design and experimental analysis of the Class-E RF power amplifier for CPT system. A 50 W power inverter was proposed for 6.78 MHz capacitive wireless power transfer system. By implementing multi-resonant oscillator, GaN MOSFET and impedance matching to the load, the efficiency of the inverter was observed. The experimental results have revealed that 50 W of power has been transmitted to an end to end system with efficiency over 81 % for the proposed Class-E RF power amplifier. Furthermore, a wireless power transfer was demonstrated successfully in the CPT system with the efficiency over 70 % for transferring power over 17 W. Improvement study of the inverter will need to be considered, especially for precision selection and fabrication of the passive components.

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Declarations

Author contribution

Conceptualization, A. Muharam, D. Obara, and M. Masuda; methodology, A. Muharam and R. Hattori; validation, A. Muharam and S. Ahmad; visualization, A. Muharam; writing–original draft preparation, A. Muharam; writing–review and editing, S. Ahmad, T.M. Mostafa, and R. Hattori; supervision, M. Masuda, A. Hapid., and R. Hattori.

A. Muharam, S. Ahmad, M. Masuda and R. Hattori has been contributed equally as the main contributor. All authors read and approved the final paper.

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Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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